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Bundled aluminum hollow-core fibers for delivery of ultraviolet laser beams

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Abstract. A bundle of aluminum hollow-core fibers is used to deliver ArF-excimer-laser light. The hollow cores are purged by a simple gas injection system to prevent the generation of ozone gas. For a 1-m-long bundle that is composed of 40 fibers each with an inner diameter of 0.7 mm, the straight loss is about 1.2 dB. The bundle also offers advantages of easy beam coupling and a high damage threshold. [DOI: 10.1117/1.2077047]

Subject terms: excimer laser; hollow fiber; fiber bundle.

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1 Introduction

ArF ($\lambda = 193$ nm) and F_2 (157 nm) ultraviolet excimer lasers have become commonly used light sources for material processing, surface engineering, lithographic techniques, and medical applications.[1–4] Although applications have been rapidly expanded, sources emitting vacuum ultraviolet (VUV) light suffer from the lack of an efficient delivery medium. Therefore, reflecting mirrors and scanning optical systems are commonly used to guide light from the source to the target.[2,3] Although some silica-glass optical fibers for delivery from ArF excimer lasers have been developed, the glass deteriorates by exposure to a high-energy-density beam.[5] For F_2 excimer lasers, with a shorter wavelength, there has been no delivery medium that is flexible and easy to handle.

Recently, we have proposed and developed hollow-core fibers to deliver UV and VUV radiation.[6,7] These hollow fibers are composed of a thin-wall glass tube with an aluminum inner coating, which is formed by metal-organic chemical-vapor deposition (MOCVD) using dimethylethylamine alane (DMEAA) as a precursor. These fibers exhibit low losses for excimer laser light because of the high reflectivity of aluminum in the UV region and the smoothness of the thin aluminum film.[6]

Usually, a lens system is used to focus a laser beam into the core of a hollow fiber that has a small diameter. Oxygen in air is oxidized into ozone, which is highly absorptive of UV light, because of a high energy density at the focused spot and in the hollow core. Therefore, an inert gas such as nitrogen or argon is introduced into the hollow core by using a complex purging and coupling system.[6,7] In addition, the beam coupling system needs to be carefully aligned because a small misalignment generates lossy high-order modes.

We propose a hollow fiber bundle for the delivery of excimer-laser light. The energy density remains low because the beam is directly coupled to the bundle without a lens. Therefore, it is expected that the gas-purging system can be made simpler. Easier beam alignment is also expected, because a focusing lens is not involved in the beam-coupling system.

2 Experiment

The ArF laser used in our experiments emits a 3.8×7.0-mm rectangular beam, and to fit the source beam, we bundled 40 hollow fibers in the shape shown in Fig. 1. The inner and outer diameters of each fiber are 0.70 and 0.86 mm, respectively, and the lengths is 1 m. The first 10 cm of the fibers are molded with an epoxy resin, and their remaining lengths are bundled using plastic sleeves to maintain flexibility.

In our preliminary experiments using the bundle, we found that the transmission loss increases gradually because of ozone generation even though the energy density is low in each core of the bundle. To address this problem,

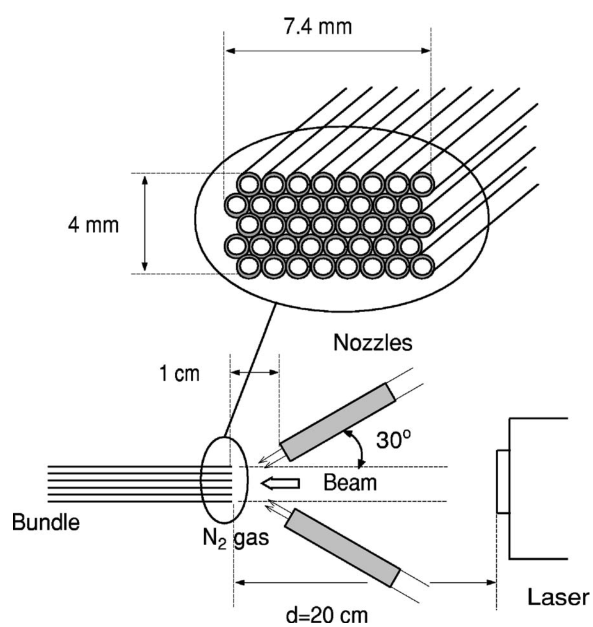

Fig. 1 End shape of the bundle and gas-injection setup.

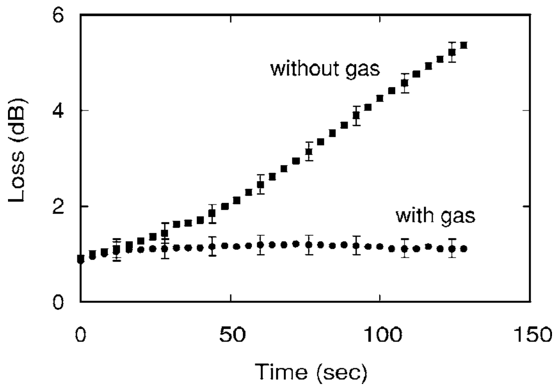

Fig. 2 Transmission losses of bundled hollow fibers as a function of ArF-excimer laser-beam irradiation time.

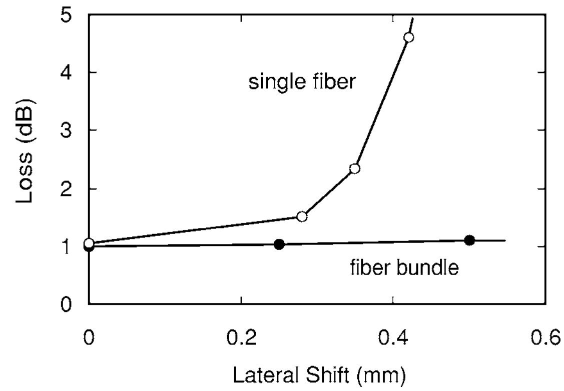

Fig. 4 Additional losses as a function of the lateral shift of the input end.

we built a simple gas-injection system, shown in Fig. 1, to introduce nitrogen from the nozzles into the hollow cores. By using this system instead of a sealed gas-purging system, which is usually used for a single fiber, we avoided additional losses caused by microbending of the fibers, which is induced by stress from a gas-introducing attachment. In addition, because no transmissive optics, such as the lens and window that are necessary for sealed systems, are included in this system, less care is needed to prevent laser-induced damage of these optics.

In the measurement, 5-mJ ArF laser pulses at a repetition rate of 10 Hz are launched into the bundle. The nozzles, with an inner diameter of 2 mm, are placed as shown in Fig. 1, and the flow rate of the nitrogen is about 500 ml/min with a back pressure of 100 kPa. Measured transmission losses as a function of the radiation time of the laser pulses for the bundles with and without gas injection are shown in Fig. 2. An inevitable coupling loss of 2.5 dB, caused by the limitation on the effective area of the hollow core region for the rectangular beam, is not included in the losses in Fig. 2. Although the loss increase in the bundle without gas injection occurs more slowly than that for a single fiber (where it occurs within a few seconds), the additional loss needs to be eliminated. With gas injection, we found that proper alignment of the nozzles successfully removes the absorption caused by the ozone and the loss is stably low at about 1.2 dB, as shown in Fig. 2. We did not see any change in the transmission after more than 100,000 pulses; thus, this bundled fiber exhibits an advantage over silica-glass fibers, which usually degrade rapidly with exposure to UV laser radiation.[8]

In the measurement of bending losses, the first 20 cm of the bundle is kept straight and the rest is bent in a constant radius of curvature by using metal jigs. Measured bending losses of the hollow-fiber bundle and, for comparison, bending losses of a single fiber are shown in Fig. 3. Small additional losses to those in the single fiber are mainly caused by localized sharp bending in the fibers of the bundle induced by friction between the fibers, and this friction can be reduced by using a lubricant.

To demonstrate the difference between a single fiber and a bundle in additional losses caused by misalignment, we measured the losses in the fibers when misalignment was intentionally produced in lateral and tilt directions at the input end of the fibers. Measured losses that occurred when the fiber axis was laterally shifted from the axis of the laser beam are shown in Fig. 4. In contrast to the single fiber, which is easily affected by a small misalignment, the loss of the bundle does not change within a 0.5-mm misalignment. The influence of tilt on the transmission loss is shown in Fig. 5. Although both the single fiber and the bundle are affected by tilting, the effect is smaller for the bundle because the unfocused parallel source beam is launched into the fibers.

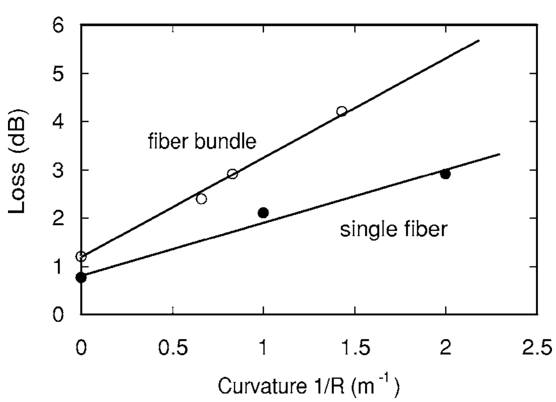

Fig. 3 Bending losses of bundled and single aluminum-coated hollow fibers as a function of curvature.

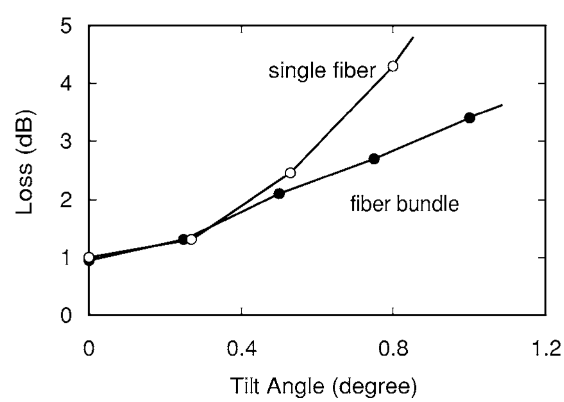

Fig. 5 Additional losses as a function of the tilt of the input end.

Table 1 Losses of bundles with different bore sizes.

Inner diameter (mm)	Length (cm)	Number of fibers	Effective core area (%)	Coupling loss (dB)	Loss (dB)
0.7	70	40	56	2.5	3.6
1.0	70	24	52	2.8	3.5

Although they have the disadvantage of higher losses, it is known that small-bore fibers have the advantages of flexibility and a small-diameter output beam. To see the effect of the bore diameter on the loss of the bundles, we built two sample bundles composed of fibers with bore sizes of 0.7 and 1.0 mm. Effective core area ratios, coupling losses caused by these effective areas, and the total losses of the bundles (including coupling losses) are shown in Table 1. The 1.0-mm fibers have an outer diameter of 1.2 mm, and the dimensions of the bundle at the input end are 4.8 and 8.2 mm. It is shown that the total loss of the 0.7-mm bundle, which is more flexible, is almost the same as that of the 1.0-mm bundle because of the large effective area of the thin-wall glass tubing. A bundle with higher flexibility and moderate losses can be fabricated by using thinner-glass-wall fibers.

Measured beam profiles at the output end of the straight bundles are shown together with a beam profile of the laser source in Fig. 6. These were observed by using a pyroelectric camera with an active area of 12.4×12.4 mm. The excimer-laser source has a beam profile with two flat peaks, as shown in Fig. 6(e). We measured output beam profiles of 0.7- and 1.0-mm bundles at distances of 5 and 15 cm from the output end of the bundles. For both fiber sizes, the traces of each fiber are diminished and the beams are more homogenized at a distance of 15 cm. The divergence angles of the output beam from those of the bundles in horizontal and vertical directions are shown in Table 2. The divergence of the output beam is larger in the vertical direction; thus, the beams become more circular at longer distances. Although we could not find a reason for this phenomenon, it is good for some applications that need a circular beam shape.

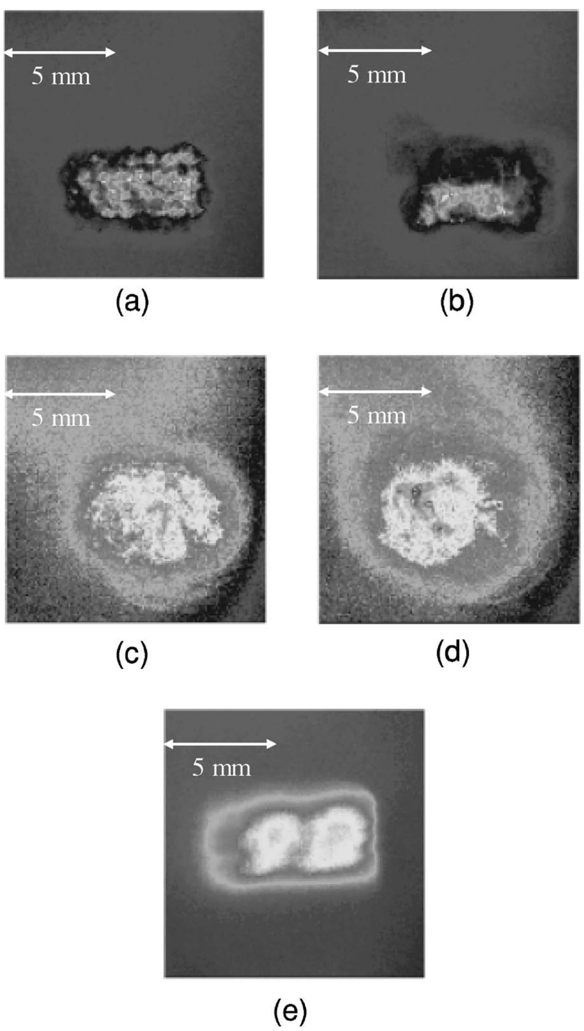

Fig. 6 Measured beam profiles: (a) 0.7-mm-bore bundle at 5 cm from the output end, (b) 1.0-mm-bore at 5 cm, (c) 0.7-mm-bore at 15 cm, (d) 1.0-mm-bore at 15 cm, and (e) input laser beam.

3 Conclusion

We proposed using bundled hollow fibers for transmission of UV and VUV laser beams. The beam coupling and gas introduction systems are simplified because the laser beam is directly coupled into the bundled fibers without a lens. In addition, the transmission loss of the bundle is less sensitive to misalignment than that of a single fiber. The straight loss of the bundle, which is composed of 40 fibers with an inner diameter of 0.7 mm, at the wavelength of an ArF laser ($\lambda = 193$ nm), is as low as 1.2 dB/m with gas injection. Output beam profiles from the bundles indicate that the beams are partially homogenized and focused. Another advantage of fiber bundles over a single fiber is a higher damage threshold because the energy density of the input beam is much lower in the fibers in the bundle.

Table 2 Beam divergence angles of bundles.

Inner diameter (mm)	Vertical divergence (deg)	Horizontal divergence (deg)
0.7	2.4	1.2
1.0	2.8	2.0

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Ozgur Yilmaz received his BS and MS degrees from the Electrical Engineering Department of Bilkent University, Ankara, Turkey, in 1999 and 2002. From 1999 to 2002 he was a spectrum engineer in the Communication and Spectrum Management Research Center at Bilkent University. He is currently pursing his PhD degree at Tohoku University, Sendai, Japan. His research interests include electromagnetic-wave propagation, electromagnetic optics, and hollow-fiber optics for UV and IR light.

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Mitsunobu Miyagi graduated from Tohoku University, Sendai, Japan, in 1965, and received his ME and PhD degrees from the same university in 1967 and 1970. He was appointed research associate at the Research Institute of Electrical Communication, Tohoku University, in 1970. From 1975 to 1977, on leave of absence from Tohoku University, he joined McGill University, Montreal, PQ, Canada, where he was engaged in research on optical communication. In 1978, he became an associate professor at the Research Institute of Electrical Communication. He spent a month at Tianjian University, China, as a consultant to the International Advisory Panel of the Chinese University Development Project and the Chinese Review Commission of the Chinese Ministry of Education in 1985. Since 1987, he has been a professor in the Department of Electrical Communications, Graduate School of Engineering, Tohoku University. From 2002 to 2004, he was the dean of the School of Engineering, Tohoku University. His research activities cover fiber optics, integrated optics, and guided-wave technology and its application in the mid-infrared, especially the design and fabrication of IR hollow fibers for high-powered lasers in industry and medicine. Dr. Miyagi is a member of the Institute of Electronics and Communication Engineers of Japan, the Laser Society of Japan, the IEEE, and the Optical Society of America. In 1989, he was awarded the Ichimura Prize for his contribution to IR hollow fibers and their application. He was also appointed an SPIE Fellow in 2001.